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IN SITU VITRIFICATION PROCESSING
OF SOILS CONTAMINATED WITH
HAZARDOUS WASTES

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INTRODUCTION

As management of hazardous materials gains increased attention in the United States, new, more effective technologies are being sought to immobilize and/or destroy the wastes either in situ for previously disposed wastes, or at the waste generation site. The new Resource Conservation and Recovery Act (RCRA) and Comprehensive Environmental Response Compensation Liability Act (CERCLA) legislation, combined with proposed rule making by the Environmental Protection Agency (EPA), is making landfill disposal very costly and is moving in a direction that will severely limit future land disposal. Further, the extended liability associated with future environmental impairment provides a significant corporate incentive to dispose and delist wastes within the plant or waste site boundary.

Pacific Northwest Laboratory (PNL) is developing a remedial action process for contaminated soils that is potentially significant in its application to these concerns. Although the process was initially developed to demonstrate a potential technology for disposal of transuranic waste contaminated soil sites, recent tests have shown that many hazardous chemical wastes are also destroyed or immobilized as a result of the treatment. The process, in situ vitrification, was originally developed for the U.S. Department of Energy and is more recently being adapted for selected commercial clients for hazardous wastes.

In situ vitrification (ISV) is a thermal treatment process that converts contaminated soil into a chemically inert and stable glass and crystalline product. Figure 1 illustrates how the process operates. A square array of four electrodes is inserted into the ground to the desired treatment depth. Because the soil is not electrically conductive once the moisture has been driven off, a conductive mixture of flaked graphite and glass frit is placed among the electrodes to act as the starter path. An electrical potential is applied to the electrodes, which establishes an electrical current in the starter path. The resultant power heats the starter path and surrounding soil up to 3600°F (2000°C), well above the initial melting temperature or fusion temperature of soils. The normal fusion temperature of soil ranges between 2000 and 2500°F (1110 and 1400°C). The graphite starter path is eventually consumed by oxidation, and the current is transferred to the molten soil, which is now electrically conductive. As the vitrified zone grows, it incorporates nonvolatile elements and destroys organic components by pyrolysis. The pyrolyzed byproducts migrate to the surface of the vitrified zone, where

they combust in the presence of oxygen. A hood placed over the processing area provides confinement for the combustion gases, and the gases are drawn into the off-gas treatment system.

Pacific Northwest Laboratory began developing ISV technology in late 1980 under the support of the U.S. Department of Energy. Since then, numerous experimental tests with varying conditions and waste types have been conducted [1,2,3,4]). Table 1 describes the different scales of test units that PNL used in developing the technology. The successful results of the 46 bench-, engineering-, and pilot-scale tests have proven the feasibility of the process. Also, economic studies have indicated that tremendous economies of scale are attainable with the ISV process [1]. These factors led to the commitment to design, fabricate and test a large-scale prototype. Its successful testing has demonstrated the field utility of the large-scale unit and has proven the initial economic projections.

This paper describes the large-scale ISV system, discusses its capabilities, and summarizes the results of testing to date. Pacific Northwest Laboratory recognizes that ISV is not the solution to all hazardous waste management problems. But judiciously applied, ISV can offer technical and economic improvements to state-of-the-art remedial action technology. With an understanding of the process design and functions, the waste manager can make sound judgements about the applicability of ISV to site-specific disposal problems.

PROCESS AND OPERATION DESCRIPTION

In situ vitrification uses the surface starting technique to establish melting of the soil. As the melt grows downward and outward, power is maintained at levels sufficient to overcome the heat losses from the surface and to the surrounding soil. Generally, the melt grows outward for a width of about 50% beyond the spacing of the electrodes. Therefore, if the electrode spacing is 18 ft (5.5 m), a melt width of about 28 ft (8.5 m) would be observed under nominal conditions. The molten zone is roughly a square with slightly rounded corners, a shape that reflects the higher power density around the electrodes.

As the melt grows in size, the resistance of the melt decreases, making it necessary to periodically adjust the ratio between the voltage and the current to maintain operation at constant power. This is done by adjusting the tap position on the primary power supply to the electrodes. There are 14 effective taps that permit adjusting the voltage from a maximum of 4000 V to a minimum of 400 V per phase and the current from a minimum of 400 A to a maximum of 4000 A per phase. Operations follow the power equation $P = I^2 \times R$, where P is power, I is current, and R is resistance.

The large-scale process equipment for in situ vitrification is depicted in Figure 2. The process immobilizes contaminated soil and isolates it from the surrounding environment. Controlled electrical power is distributed to the electrodes, and special equipment contains and treats the gaseous effluents.

The process equipment required to perform these functions is divided into five major subsystems: 1) electrical power supply, 2) off-gas hood, 3) off-gas treatment, 4) off-gas support, and 5) process control.

Except for the off-gas hood, all components are contained in three transportable trailers (Figure 3): a support trailer, a process control trailer, and an off-gas trailer. All three trailers are mounted on wheels sufficient for a move to any site over a compacted ground surface. The off-gas hood and off-gas line, which are installed on the site to collect the gaseous effluents, are dismantled and placed on a flatbed trailer for transport between the sites to be treated. The effluents exhausted from the hood are cooled and treated in the off-gas treatment system. The entire process is monitored and controlled from the process control trailer.

The off-gas trailer is the most complex and expensive of the three trailers. The off-gas treatment system cools, scrubs, and filters the gaseous effluents exhausted from the hood. The primary components include: a gas cooler, two wet scrubber systems (tandem nozzle scrubbers and quenchers), two heat exchangers, two process scrub tanks, two scrub solution pumps, a condenser, three mist eliminators (vane separators), a heater, a particulate and charcoal filter assembly, and a blower system.

A major element of the off-gas support system is the glycol cooling system, which is mounted on the support trailer. This system interfaces with the scrub solution and extracts the thermal energy that builds up in the off-gas treatment system from cooling the combustion gases from the hood. The heat is rejected to the atmosphere in a fin tube, air-cooled heat exchanger. This makes the entire process system self-sufficient in terms of site services, except for electrical supply. In cases where electrical supply is remote and costly to bring in, diesel generators can be used to supply the required electricity. Details of the large-scale process equipment and the process capabilities are found in Buel and Carter [3].

The normal processing rate for the large-scale system is 3 to 5 tons per hour or nominally 3 to 5 yards per hour, a rate competitive with many other remediation technologies. The average processing operation lasts about 150 to 200 hours depending upon the depth and electrode spacing, although for processing to depths of 50 ft, single processing operations can range from 300 to 400 hours. The production rate will remain constant at 3 to 5 tons during the entire time period, resulting in a vitrified mass greater than 1,000 tons.

For routine operations on a site, all three trailers are coupled together and moved from one processing position to another by pulling them as a unit. ~~The hood is moved from one position to another with a crane. The crane is~~ also used to assist in coupling and uncoupling the off-gas lines. Moving from one processing position to another takes about 16 hours; thus, a relatively high operating efficiency can be achieved. This 16-hour interim for movement also provides time for performing routine maintenance.

PRODUCT CHARACTERISTICS

The ability of the waste form to retain the encapsulated or incorporated heavy metals is of prime importance to the usefulness of the ISV process.

The vitrified waste form has been subjected to a variety of leach tests, including the EPA's Extraction Procedure Toxicity Test (EP Tox) and Toxic Characteristics Leach Test (TCLP). All of these tests show a uniformly low leach rate for heavy metals of about 1×10^{-4} lb/ft²/day (5×10^{-5} grams/cm²/day) or lower. Based on limited tests, it is reasonable to assume that the vitrified material can be delisted under the provisions of either the EP Tox or the TCLP.

Another indication of the durability of the ISV waste form is found in a study of the weathering of obsidian, a glasslike material physically and chemically similar to the ISV waste form [5]. In the natural environment, obsidian has a hydration rate constant of 0.0016 to 0.03 mil² (1 to 20 μm^2) per 1000 years [6]. Using a linear hydration rate of 0.016 mil² (10 μm^2) produces a highly conservative estimate of a $\ll 40$ mil (1 mm) hydrated depth for the ISV waste form over a 10,000-year time span.

Data for the release of sodium from vitrified Hanford soil during a leach test at 90°C are available [1] for durations of 7, 14, and 28 days. Because the sodium is soluble in the leachate, its normalized release is a measure of the extent of hydration of the glass and, in particular, its normalized release divided by the density of the glass is the depth of hydration. If the glass is assumed to hydrate according to the same parabolic rate law as has been found for obsidian, then the square of the depth of hydration divided by the duration of the test should be constant. Using the data in Buelt et al. [1], the result of this calculation increases between the 7- and 14-day data, but then is constant between the 14- and 28-day data. Taking this final value and using the density of the glass, the hydration rate at 194°F (90°C) appears to be about 0.0032 mil² (2 μm^2 /yr). In the literature on field studies of obsidian hydration, the rate is found to obey an Arrhenius relation with an activation energy of 20 kcal/mole [6]. Applying this to the ISV glass hydration, we can predict rates of 0.008 mil² (5 μm^2)/1000 yr at 77°F (25°C) (e.g. for glass exposed to the air) and 0.0016 mil² (1 μm^2)/1000 yr at 50°F (10°C) (e.g. for glass buried underground). These values are comparable to those found for obsidian hydration rates in the field for similar average weathering temperatures.

The long-term stability of obsidian in nature is controlled by three mechanisms [5]: alteration (weathering), devitrification (recrystallization) and hydration (water absorption) [6]. Review of the literature indicates that the usual controlling mechanism is devitrification. Studies of the mean age of natural glasses indicate that obsidian has a mean life of about 18 million years [5]. Considering the similarity of the ISV waste form to obsidian, it is reasonable to postulate that the mean life of the vitrified material would be on the order of 1 million years.

The ISV waste form is a glass with the atomic structure that is random, rather than the highly structured nature of a crystalline material. This

leads to another benefit: the fracture mechanism is conchoidal, which means that the waste form is not subject to significant damage by freeze/thaw mechanisms that can accelerate natural degradation. Accelerated fracturing by alternately freezing and thawing would increase the surface area and the amount of material that could be leached into groundwater.

ECONOMIC ANALYSIS

The economics of the process have been examined under various conditions typical of those that might be encountered throughout the United States. The methodology for the ISV cost estimates has been developed and reported [1] for a large-scale system. The approach and estimates have been validated by actual design, fabrication, and operational testing of the large-scale system. Key features of the economic projections were: 1) that the system could be operated with two people per shift, and 2) that the system could be moved from one processing area to another processing area in less than 24 hours. Both of these assumptions have been proven correct [2].

Highlights of the cost estimate technique used for the cost projections are summarized here; details can be obtained from the original reference [1]. The cost estimate is divided into five main categories: 1) site costs, 2) equipment cost, or capital recovery, 3) operations and labor, 4) electrode costs, and 5) electrical costs. The factors that most significantly affect total cost are the amount of moisture in the soil, labor rate costs, and the cost of electricity. The amount of moisture directly affects operational time and, therefore, has a direct bearing on the labor and operations costs. The electrical energy equivalent of the heat of vaporization for the moisture in the soil must be supplied and the water boiled off before vitrification can proceed. The cost of labor and electrical power also has a direct effect on the operational costs. Equipment or capital recovery costs and electrode costs are significant; however, they are treated as constants. Site costs are based on nominal amounts of civil work that must be performed, which include acquiring and placing clean backfill in the subsidence zone.

Equipment costs or capital recovery include the costs of the ISV system and the necessary support equipment such as a front loader and crane for earth-moving operations and for moving the hood and trailers, respectively. There is also a nominal allowance for extending existing power lines and installing a substation. All equipment is assumed to have a 10-year life. The sum of the equipment costs is multiplied by a 20% capital recovery factor and added in as a unitized cost factor.

Operations and labor costs consist of the labor and materials for those activities that must be performed to support normal operations. ~~These activities include labor time for the two operators required to operate the system.~~ System operation is calculated on the basis of 24-hour continuous operations. Other support activities include digging the holes and placing the electrodes, moving the trailers and hood from one processing position to another, and performing routine maintenance operations when the system is being moved. Also included are costs for placing the starter material, and connecting,

disconnecting, and testing the electrodes. The operational cost also includes an allowance for secondary waste disposal, i.e., treating and/or disposing the scrub solution once per week.

Electrode costs represent the purchase of electrode materials, which are used only once, assuming that the electrodes are left in the melt. For operations in a chemically hazardous environment, the electrodes can be retrieved and sold for salvage value, which is about 20% of the original cost. For operations with a process sludge where significant decomposition of the sludge occurs, there is a potential for electrode reuse; however, estimating electrode recovery values that are higher than the salvage value is not conservative planning at this time.

These cost factors have been calculated and plotted in graphical form as shown in Figure 4. A maximum cost for the various soil and moisture cases in Figure 4 occurs at \$.0825/kWh. This maximum cost for electricity will fluctuate with the price of diesel fuel; however, the indicated value is realistic in today's economy. At local electrical rates that are higher than this value, the use of portable diesel generator power is recommended. Whether the units are rented or purchased depends on the length of the remediation operation and business decisions regarding future operations. The flat rate can also be used for planning for sites where local electrical power is unavailable and bringing in a power line would be very expensive. The case for wet industrial sludges was included to cover those situations where consolidation and immobilization at an active plant site was the primary objective. This may be important to the typical owner/generator who has sludge surface impoundments that must be closed and the owner/generator does not want to incur the long-term liability and costs associated with shipping to a secure landfill.

PROCESS PERFORMANCE

The discussion of process performance is divided into two sections: 1) experience with hazardous wastes, and 2) applications considerations. This discussion will focus on the overall treatment efficiency, that is, the retention and/or destruction in the melt and the capture and removal of the material released from the melt by the off-gas system. The sum of the two functions represents the overall system Destruction Removal Efficiency (DRE).

HAZARDOUS WASTE EXPERIENCE

The results of the process performance testing with hazardous materials are subdivided into two categories: metals and organics.

Metals

During the processing operations with ISV, metals are either dissolved in the glass or incorporated in the vitreous matrix. The three factors that have the largest effect on retention are burial depth, solubility, and vapor pressure. Burial depth has a direct function on retention, increasing the amount of retention with increased burial depth. Metals are retained in the melt as a direct function of the solubility and inversely proportional to their vapor pressure.

The measure of the material retained in the melt is the retention factor, defined as:

$$\text{Retention Factor} = \text{RF} = [A]_i/[A]_e$$

Where, $[A]_i$ is the concentration of the element A initially present and $[A]_e$ is the concentration of element A exiting the component. This terminology is used for the retention in the melt as well as the retention in the off-gas treatment system. The retention factor is the inverse of the quantity [1-DRE].

The effect of burial depth on retention of elements is charted in Figure 5. In these pilot-scale tests, the metals were in common chemical forms such as nitrates, fluorides and oxides. Figure 6 shows the results of the engineering-scale tests with lead and cadmium. The lead shows a constantly higher retention in the melt with increasing depth, most likely reflecting the high solubility of lead in glass. Cadmium, which is less soluble in glass, also shows a depth-dependent retention. When estimating retention factors for metals in the melt or off-gas system, the solubility of the metal in the glass and also the likely oxidation state should be considered. The melt is reducing in nature, so the most likely form of most metals is either the pure state or the lowest oxidation state that will accommodate a stable oxide. Data from other glass processes, such as melters, is not considered a reliable source in estimating retention factors, because of the difference in reducing conditions in the glass. Ruthenium in an oxidizing environment can form RuO_4 which sublimates at about 1830°F (1000°C) and cause serious problems in melter off-gas treatment systems. In the pilot-scale radioactive test, ruthenium exhibited a retention of 99.82% or a retention factor of 550. The enhanced retention because of oxidation state and solubility is very important when assessing potential applications to traditionally volatile metals.

Retention factors measured in pilot-scale testing are shown in Table 2 for both the melt and the off-gas treatment system. These data are sufficient to infer the retention of other hazardous metals. Results for large-scale testing show that retention continues to increase with increasing depth below 3.3 ft (1 m). An order of magnitude increase in retention was observed when the depth was increased from 3 to 16 ft (1 to 5 m) [2]. The presence of combustibles can provide a path to the surface by entraining the metals in the combustion product or pyrolytic gases, increasing the retention fraction. The closer to the surface, the less likely the entrained material will not be scrubbed out by the molten glass and recaptured. Even the decomposition of nitrates can provide an elution path if the reaction occurs near the surface.

Enhanced releases associated with combustion events are shown in Figure 7. These results are also from pilot-scale tests where the metals were deliberately placed with combustibles. At each combustion event, the concentration of the metals in the scrub solution increases measurably with a clear change in the slope of the concentration curve.

These data are important for estimating the amount of secondary waste that will be generated by contaminating the scrub solution with hazardous chemicals, necessitating potential treatment of the scrub solution before its

disposal. With a meter of clean overburden, retention factors of at least 100 can be expected even for the volatile elements. Retention factors of 1,000 and greater can be expected for the semi- and nonvolatile metals, assuming that there is no significant quantity of combustibles.

Organics

During processing, organics that are contacted by the vitrified material are destroyed by pyrolysis. The pyrolytic gases move upward through the melt and combust when contacted by the oxygen atmosphere in the hood. The data base for processing organics has been limited to selected organics in containers, PCBs, dioxins and organics associated with electroplating wastes. As the ISV process gains additional acceptance as a remediation tool, the data base will grow through feasibility tests, field demonstrations, and actual remediation applications.

Combustible testing with organics has included up to 110 lb (50 kg) of solid combustibles and 50 lb (23 kg) of liquid organic in a single pilot-scale experiment. The materials were packaged in a container such as what might be found in a solid-waste burial ground. Chromatographic, sample bomb, and mass spectrometric analyses of the effluent from both the hood and the exhaust stack showed less than 5×10^{-3} vol% release for light hydrocarbons during peak combustion periods. This level of release indicates nearly complete pyrolysis and combustion [7]. A limited number of experiments have been conducted to define the pressure rise and rate of release associated with organics in sealed containers. Theoretical calculations predicted that the internal pressures would be several hundred psi, and that the pyrolyzed material would produce a transient pressure wave that would move through the melt in a few seconds. The tests were performed using the engineering-scale system; the sealed containers were equipped with pressure sensors. The maximum pressure observed was 32 psig. The pressure attenuated over a brief period of about 1 minute; however, the organic contents in the containers were slowly released over a period of a few minutes (<10) to up to 90 minutes [8]. These data indicate that the metal softened as the vitrified zone approached the sealed container, and that the intrusion of the glass was slower than the theoretical maximum rate. This could be a scaling effect, related to the relatively high viscosity of the glass and smaller size of the container. Intrusion into a buried 55-gallon drum is expected to be more rapid; however, effective destruction is expected by the extensive molten soil of a large-scale melt.

An engineering-scale test was conducted using soils contaminated with 500 ppm of PCBs. The data from the test showed that the process destruction was slightly greater than 99.95% [9]. The small amount of material released to the off-gas system was effectively removed, yielding an overall system DRE of >99.9999%. Analysis of the vitrified block showed that there were no residual PCBs; considering the processing temperature, the data are reasonable. The soil adjacent to the vitrified area was examined for PCBs; limited quantities were detected (0.7 ppm of PCBs). These data indicate that the vitrification rate is greater than the PCB diffusion rate and that migration away from the vitrification zone during processing is not a significant concern. The overall results were sufficiently promising that a pilot-scale test has been

authorized. The scope of the test will use 1000 ppm PCB-contaminated soil and be performed in accordance with a TSCA permit issued by EPA Headquarters.

A similar bench-scale test [10] was performed on soils contaminated with dioxin (2, 3, 7, 8 TCDD). The results gave a destruction efficiency for the ISV process alone of greater than 99.995% based on analytical detection limits. Additional off-gas removal with a conventional off-gas treatment system that utilizes a carbon filter would result in an overall DRE of >99.99999% for dioxin. No dioxins or furans were detected in the off-gas emissions during the test. These data confirm and support the PCB results and indicate that ISV is a highly potential process for treatment of chlorinated organic contaminated soils.

Engineering-scale tests on electroplating wastes have shown that the destruction efficiency for contaminated soils is >97% for the process even when the contaminated soil is not covered with a layer of clean soil. Other tests have shown that an uncontaminated layer of soil increases the efficiency of the process to greater than 99.99%. Additional removal can be obtained by the use of charcoal filters in the off-gas treatment system, thus improving the overall system DRE.

The observed system DREs indicate that the process has a potential to be a very valuable tool for the remediation of sites that contain both organic and metallic hazardous wastes. While the results are promising, feasibility testing to confirm applicability is strongly recommended prior to any commitment to deploy the process on a site that contains significant quantities of organics that are unconfined in the soil column.

APPLICATIONS CONSIDERATIONS

Before to exploring various hazardous waste application scenarios, the operational capabilities and limitations of the large-scale system will be reviewed. The capabilities of the large-scale system to treat various soil characteristics and inclusions can logically be divided into two categories: 1) capabilities of the power supply system, and 2) capabilities of the off-gas system to maintain a negative pressure during transient events. The capabilities of the electrical system in terms of electrode width, depth and shape have been reported in References 1 and 2.

The two factors that can influence the ability of the power supply system are the presence of groundwater and buried metals. As a general rule, soils with low permeabilities do not inhibit the ISV process even in the water table because the rate of recharge is not significant in terms of the processing rate. The melt proceeds at a rate of about 3 to 6 inches per hour. Thus, soils with permeabilities in the range of 10^{-5} to 10^{-9} cm/sec are considered vitrifiable even in the presence of groundwater or in the water table. Soils with permeabilities in the range of 10^{-5} to 10^{-4} cm/sec are considered marginal. Soils with permeabilities higher than 10^{-4} cm/sec are difficult to vitrify in the water table unless additional steps are taken, such as drawing the local water table down by pumping, and installing underground barriers. This is not considered a significant impediment because it is highly unlikely that any single method would be used to completely remediate a site. For example,

ISV might be used to destroy/immobilize the source and standard pump and treat methods used to cleanup plumes that have migrated from the source.

The presence of buried metals can result in a conduction path that would lead to electrical shorting between the electrodes; however, the processing margins are quite generous. Buried metals that occupy up to 90% of the linear distance between the electrodes can be accommodated without suppressing the voltage between the electrodes. Also, once melted, the impact of the metal is less significant. Miscellaneous buried metal, such as drums, should have little or no effect on the ability to process a candidate site. Metal limits are currently 5 wt% of the melt. This is a large fraction when considering drums of waste. In fact, drums containing hazardous and/or classified wastes can be placed in an array that will take advantage of the melt configuration. Such an array is shown in Figure 8. Here, the metal content of the 273 drums is 1.5% of the melt weight, leaving considerable capacity for miscellaneous metal contained within the drums.

Capacity of the off-gas system to maintain a negative pressure during processing, thus preventing the spread of contamination or resulting in fugitive emissions, is a function of the gas generation rate within the processing area. Gas generation resulting from the decomposition of humus and other natural chemicals within the soil are considered insignificant. Generic gas generating situations are shown in Figure 9. These represent the intrusions of the molten glass into void spaces. Such intrusions result in release of the entrapped air, penetration of a drum that contains combustible materials, and intrusion into soil inclusions that contain combustible materials, either solids or liquids. Schematically, the capacity of the off-gas system to contain the gas resulting from the processing event is shown in Figure 10. The varying capacities represent what might be encountered in a solid-waste burial ground. The release of the gas is a transient event, ending in about 1 minute. Therefore, once the transient event has passed, the system still has the capacity to handle another transient event. The events are time-order limits, not cumulative capacities.

The ISV process is particularly well suited to in-place disposal of hazardous waste. The toxic heavy metals are encapsulated or incorporated into the glass, and the organics in containers are destroyed. Certain inorganic compounds such as nitrates are also destroyed by reducing the compound to the diatomic gases by the temperature and reducing conditions of the melt. Sulfates are partially decomposed; the remainder can easily be removed by the off-gas treatment system. Fluorides are dissolved into the glass to 98% for source terms of several hundred ppm. Chlorides are dissolved to the limits of solubility, which are much less than those for fluorides, but up to 1 wt% of the melt, which can be a large quantity. The fluorides and chlorides not dissolved in the glass can be scrubbed out by the off-gas treatment system, using a caustic scrub solution.

There are five general areas where the ISV process might be applied to mixed hazard waste: 1) contaminated soil sites, 2) burial grounds, 3) tanks that contain a hazardous heel in the form of either a sludge or salt cake, 4) classified waste that is already containerized or amenable to containerization, and 5) process sludges and tailings piles. The application of the ISV

process to contaminated soil sites and burial grounds is similar to the previously discussed application to general soil and burial ground sites, with the same processing limits for metal and combustibles.

The use of ISV to destroy the hazardous heel in tanks has been tested on the engineering scale with chemical salts. The results of the feasibility study showed that the release was within acceptable limits for the off-gas system and that a vitreous mass was formed. The original tests were performed using additions of glass formers during the processing to achieve a vitreous waste form. The data could be extended to a scenario to dispose the residual heel and the tank, and to immobilize contaminated soil in the immediate vicinity of the tank. By adding soil and/or rock backfill, the tank could be filled with glass-forming materials prior to processing. This technique could eliminate the concerns of tank dome and/or wall collapse identified during the original testing. Techniques for filling to the peak of the tank dome have been developed. Electrodes would be inserted into the tank through existing openings. The vitreous area would grow downward and outward, encompassing the tank, the contents, and a portion of the surrounding soil. Estimates of the maximum size tank have not been completed, but tanks from 100,000 to 300,000 gallons could be permanently disposed by this technique. The metal content of the tank structure should not impose a processing limit.

Process sludges and tailing piles that contain natural radioactive materials and hazardous chemicals can be disposed using the ISV process. Applications that involve natural radioactive elements that result in relatively high radon fluxes at the surface are considered potential candidates for remediation by ISV. Tests with zirconia-lime sludges [11] showed that the material was able to be vitrified and the radon emanation level was reduced by a factor of 10^4 to 10^5 after processing. This is a practical solution where the radon emanation levels are high, the wastes also contain hazardous chemicals that could be leached into the groundwater, and the local infiltration rate is high. In contrast, for large piles in remote areas and where the infiltration rate is very low, barriers over the pile have been shown to be quite effective in preventing the release of hazardous chemicals. Each potential application must be examined on its own merit.

Valuable land that is contaminated can be reclaimed by the use of ISV processing, converting a corporate liability to a capital asset. Old transformer areas and capacitor storage and repair areas that are now in the business district, but contaminated with PCBs, are examples of this concept. The ISV process has been shown to be effective on PCB-contaminated soils, achieving a system destruction removal efficiency (DRE) of 99.9999%.

Other applications considered, but not yet developed, include shaft sealing, foundations and erosion barriers for remote locations, and the generation of impermeable barrier walls to prevent groundwater seepage into a site. Barrier generation is considered an interim solution that would mitigate an existing hazardous situation until a final solution could be implemented.

SUMMARY OF PROCESS STATUS AND BENEFITS OF APPLICATION

The ISV process has been demonstrated at field-scale conditions, thus eliminating uncertainties of scale-up. This is significant because scale-up is the major risk area in the development and deployment of a new technology. Technology adaptation is a much smaller investment risk than technology development. The applicability of the ISV process to a particular waste can be determined with existing ISV equipment for a few thousand dollars. Thus, feasibility testing is relatively inexpensive. The focus of the feasibility testing is on the performance requirements for the off-gas treatment system and the type and quantity of secondary waste generated. It has already been shown that almost all of the soils encountered can be vitrified, so this is not a consideration during most feasibility testing.

The experience to date indicates that the process is ready for deployment for soil sites contaminated with heavy metals and inorganics. Experience with low boiling point organics that are uncontaminated in the soil column is very limited, and feasibility testing with actual site samples prior to application is strongly recommended. The experience with PCBs, process sludges, and plating wastes is very encouraging. It is anticipated that the ISV process will be used for a broader application of waste management problems. It is also recognized that no single treatment process is applicable to all waste management needs. Within this context, ISV is a new and powerful tool that should be considered and evaluated for radioactive, mixed hazardous, and hazardous chemical applications that fall within the treatment capabilities of the process.

Specific benefits inherent in the ISV process are:

- Safety for workers and public
- Long-term durability of the waste form (>1 million years)
- Applicability to a variety of soils
- Cost effectiveness (\$100-\$250/ton for soils)
- Volume reduction for sludges (<\$100/ton)
- Efficient processing rates (3-5 tons/hr)

In summary, the ISV process is cost-effective, applicable to a wide variety of soils and wastes, and responsive to the regulatory changes that emphasize the need for on-site treatment and remediation.

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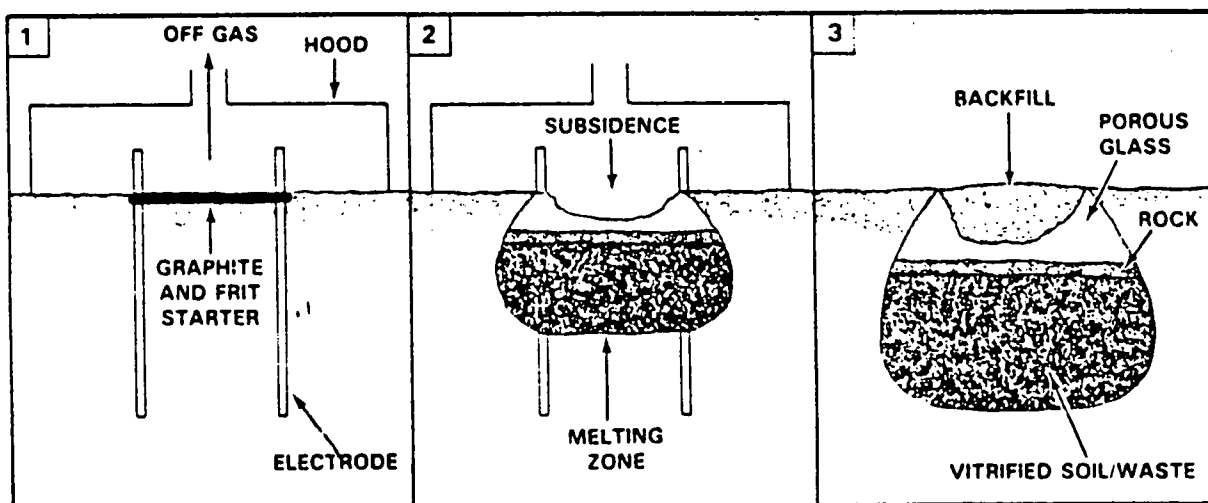


FIGURE 1. The In Situ Vittrification Process

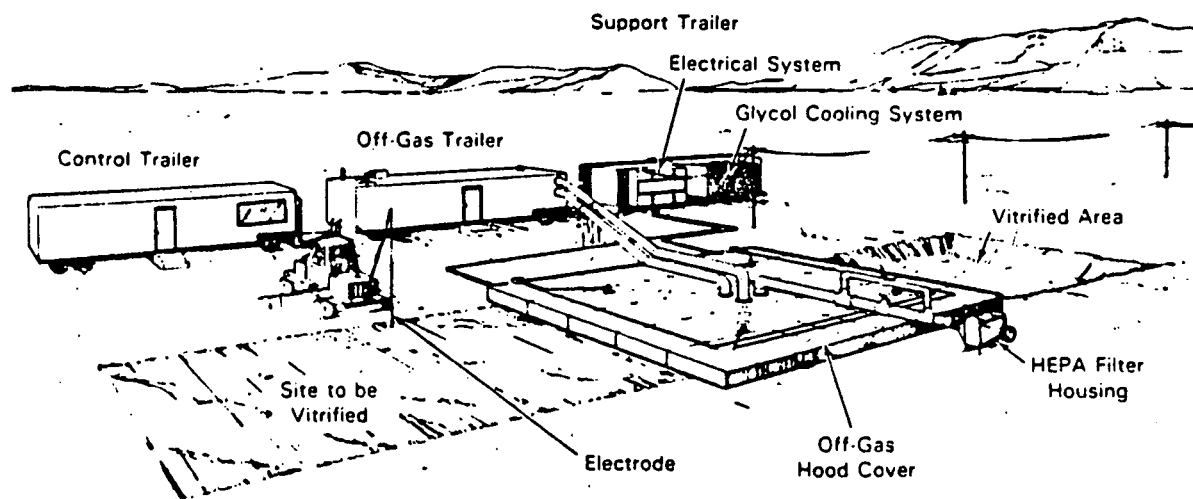


FIGURE 2. Setup for In Situ Vitrification

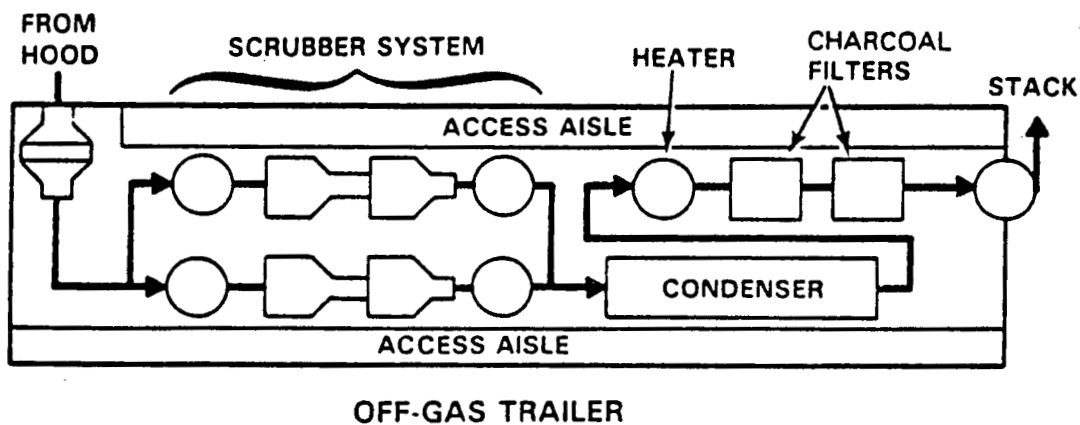
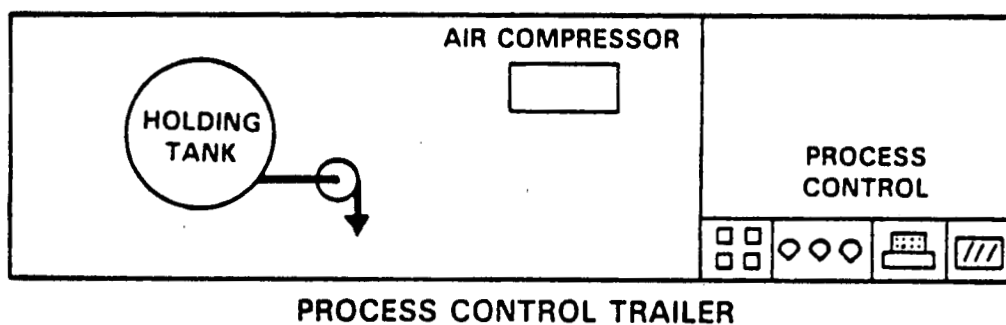
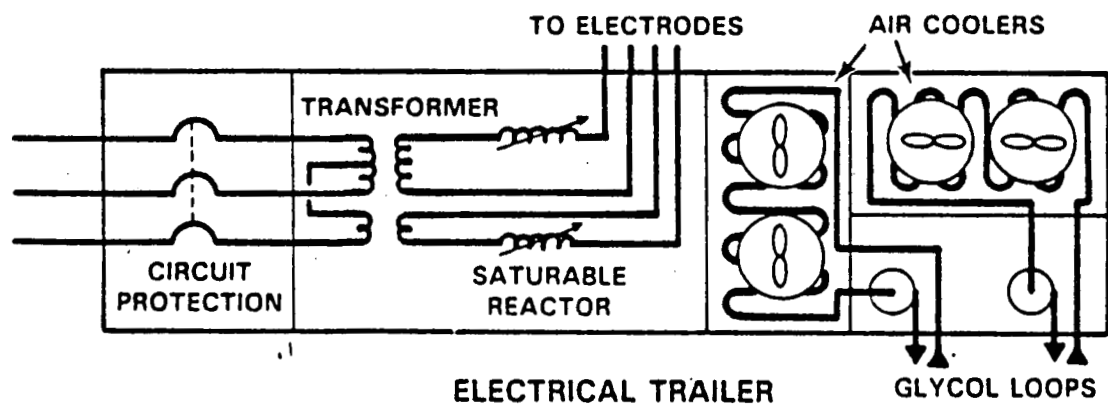


FIGURE 3. Process Trailers for the Large-Scale In Situ Vitrification Unit

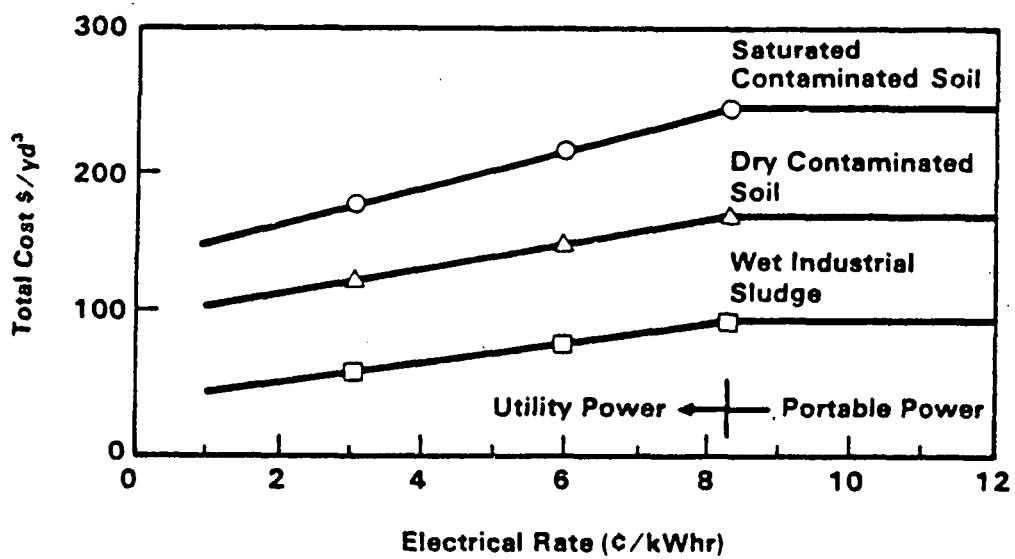


FIGURE 4. Cost of ISV Applications

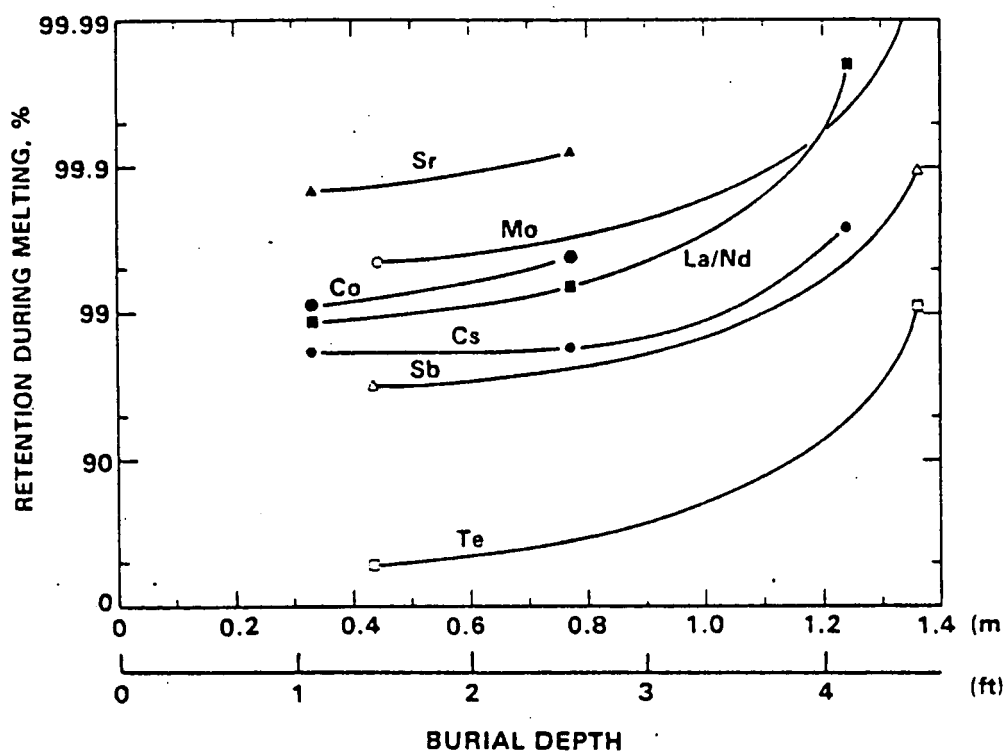
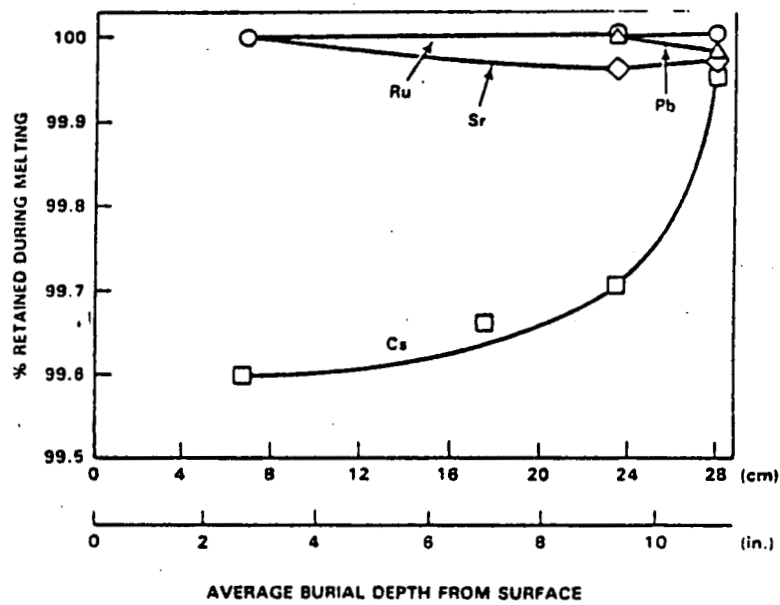
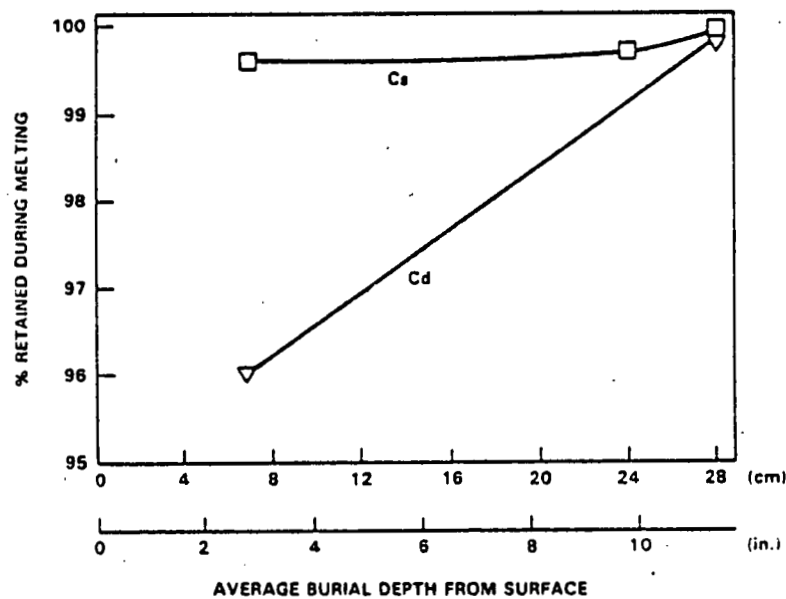


FIGURE 5. Element Retention Versus Burial Depth During Pilot-Scale Tests



(a)



(b)

FIGURE 6. Element Retention Versus Burial Depth During Engineering-Scale Tests: (a) shows ruthenium, strontium, lead, and cesium; (b) shows cesium and cadmium.

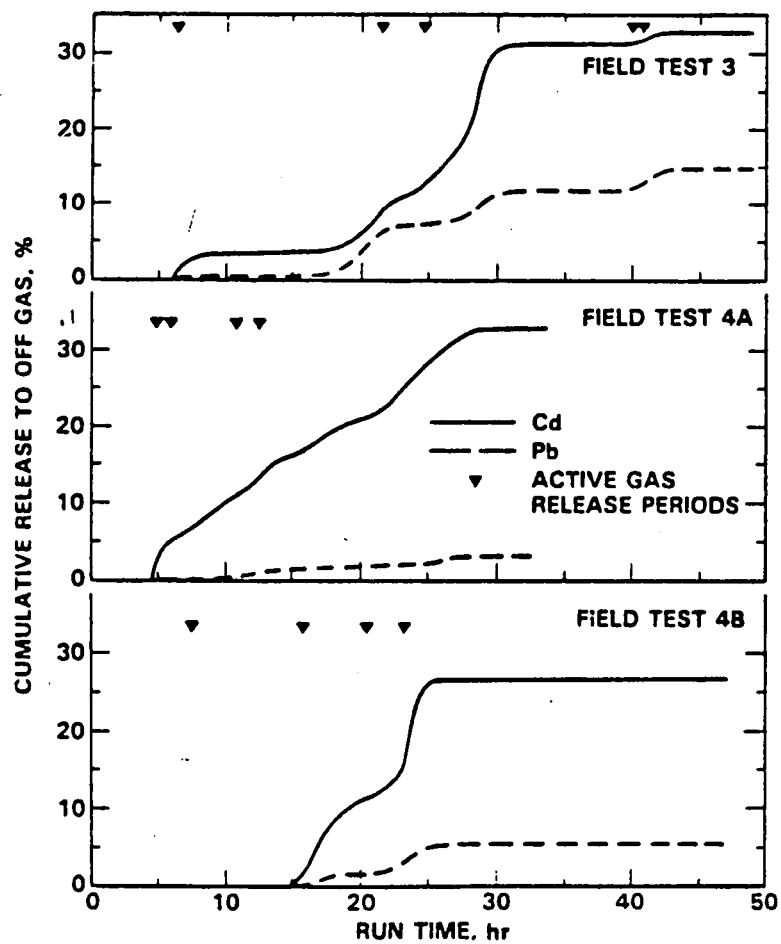
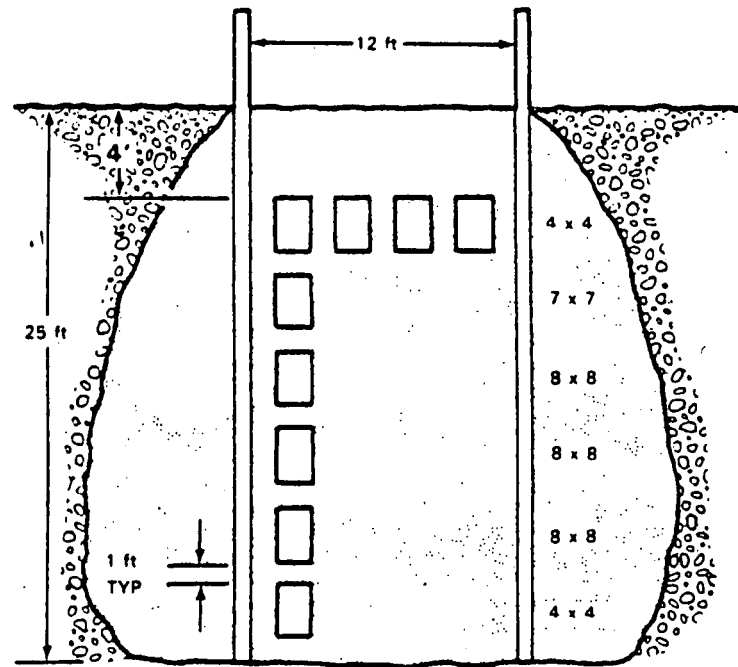


FIGURE 7. Cadmium and Lead Release as a Function of Run Time

ACCEPTABLE CONDITIONS: 90% LINEAR DISTANCE & 5 wt%



METAL wt = 1.5% OF MELT MASS

FIGURE 8. Use of In Situ Vitrification for Buried Metals

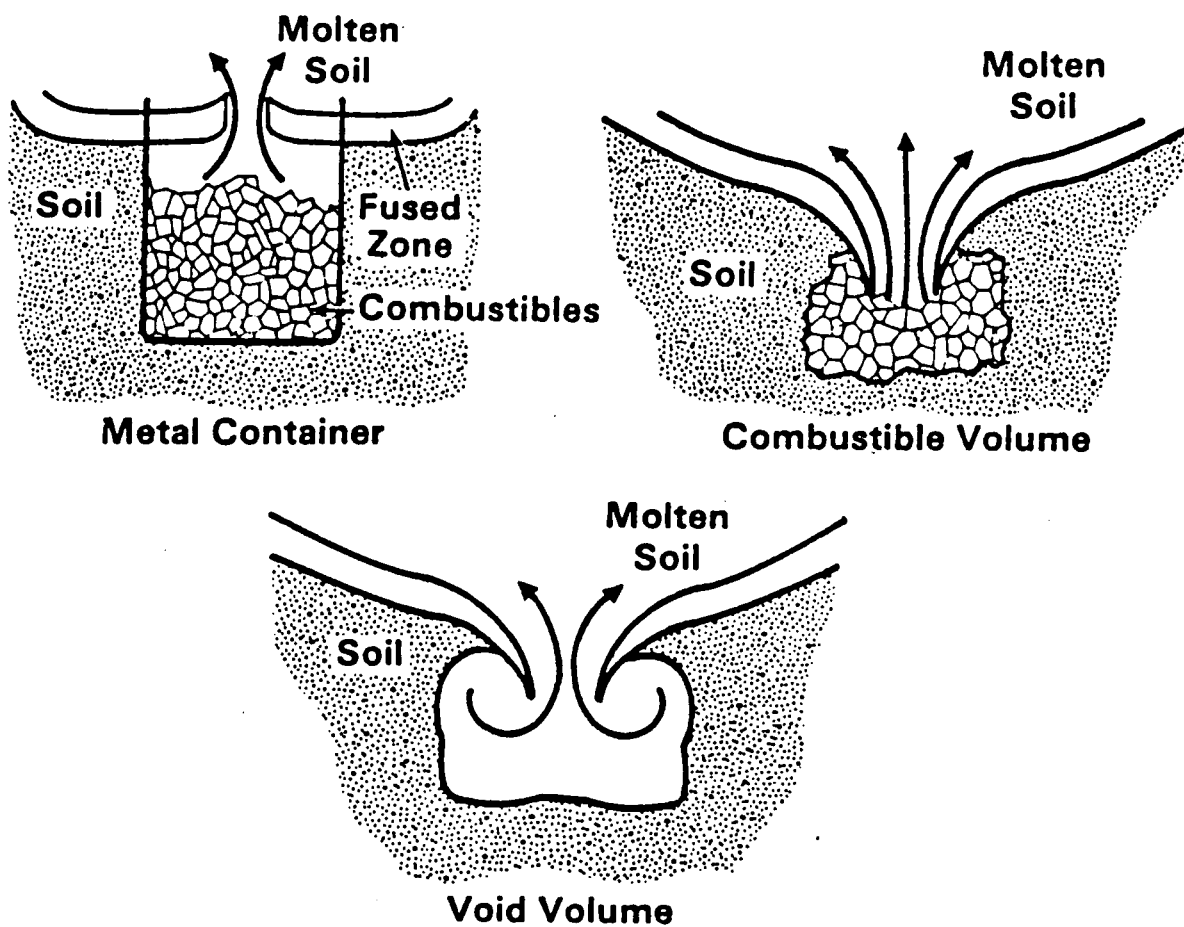


FIGURE 9. Gas-Generating Configurations

TABLE 1. ISV Test System Characteristics

<u>System, Scale</u>	<u>Power, kW</u>	<u>Electrode Spacing, ft</u>	<u>Vitrified Mass per Setting</u>	<u>Number of Tests</u>
Bench	10	0.36	2 to 5 lb	5
Engineering	30	0.75 to 1.2	0.05 to 1.0 ton	25
Pilot	500	3.0 to 5.0	10 to 50 ton	16
Large	3,750	11.5 to 18.0	400 to 800 ton	5

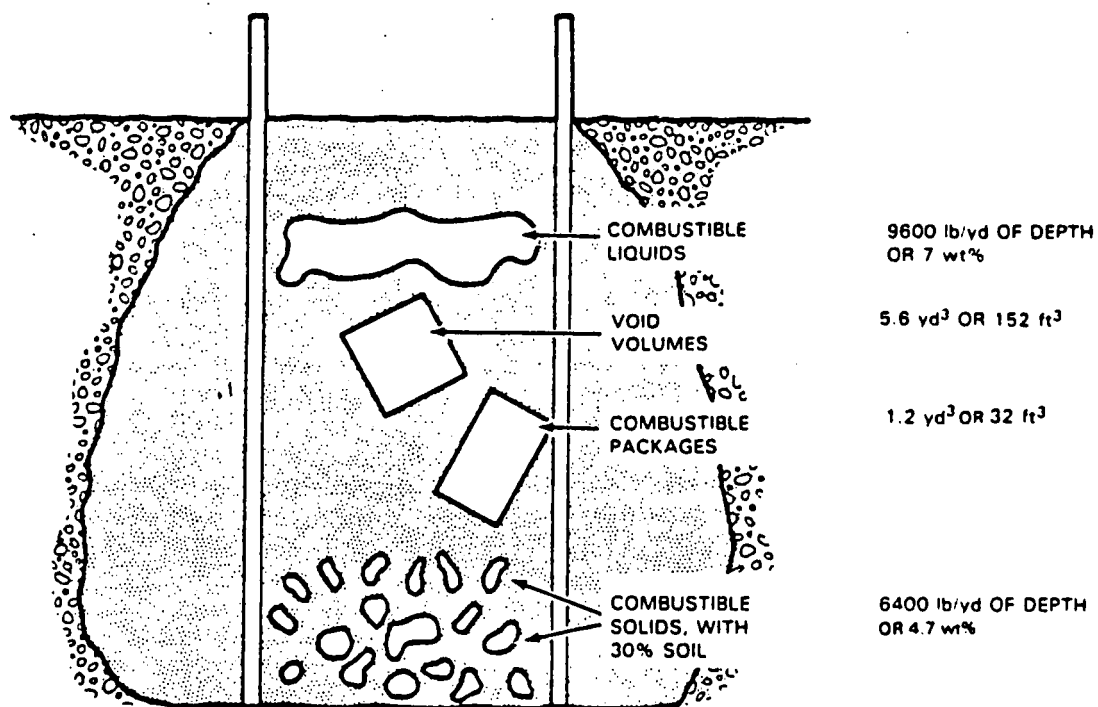


FIGURE 10. Combustible Limits for In Situ Vitrification Processing

TABLE 2. Retention Factors of Metals

<u>Type of Metal</u>	<u>Soil</u>	<u>Off-Gas</u>	<u>Combination</u>
<u>Particulates</u>			
Sr, Pu, U, La, Nd	10 ⁴	10 ⁵	10 ⁹
<u>Semi-Volatiles</u>			
Co, Cs, Sb, Te, Mo	10 ²	10 ⁴	10 ⁶
<u>Volatiles</u>			
Cd, Pb	2-10	10 ⁴	10 ⁵